Charged Pion Electroproduction in Hall C

Dave Gaskell

JLab

Hall C Summer Workshop

September 12, 2003

- Pion Form–Factor (F_π)
- Nuclear Pions (NucPi)
- Future Measurements (12 GeV, etc.)

Charged Pion Production Experiments

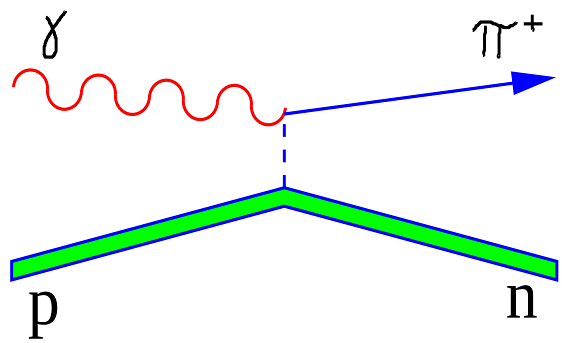
- F_π - Fall 1997: Henk Blok, Garth Huber, and Dave Mack spokespersons
  - $\rightarrow$ Primary goal was to measure the charged pion form–factor by measuring the $-t$ dependence of σ_L
  - $\rightarrow$ Two thesis students: Jochen Volmer (F_π) and Kelley Vansyoc ($G_{\pi NN}$)
  - $\rightarrow$ Phys.Rev.Lett.86:1713-1716,2001 (Form–factor): TopCite 50+!
  - $\rightarrow$ π^-/π^+ ratio analysis nearly finalized - short paper on the way
  - $\rightarrow$ Long paper?

- NucPi - Winter/Spring 1998: Hal Jackson spokesperson
  - $\rightarrow$ Measure modifications to the nuclear pion cloud via measurements of σ_L on H, ^{2}H, ^{3}He, and ^{4}He
  - $\rightarrow$ Two thesis students: Steve Avery and Dave Gaskell
  - $\rightarrow$ Phys.Rev.Lett.87:202301,2001 (Longitudinal ratios)
  - $\rightarrow$ Phys.Rev.C65:011001,2002 (separated ^{3}He$(e,e'\pi^+)^3$H cross sections)
  - $\rightarrow$ Long paper?

F_π by Pion Electroproduction

Without an e-π collider, F_π can only be determined at $Q^2 \geq 0.5$ via pion electroproduction.

The target is the virtual pion cloud of the proton:



For unpolarized $p(e, e'\pi^+)n$ scattering

$$\frac{d\sigma}{dt} = \sigma_T + \epsilon\,\sigma_L + \epsilon \cos 2\phi\,\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\,\sigma_{LT}$$

and for small -t, σ_L dominates because the interference terms vanish and due to the proximity to the pion pole:

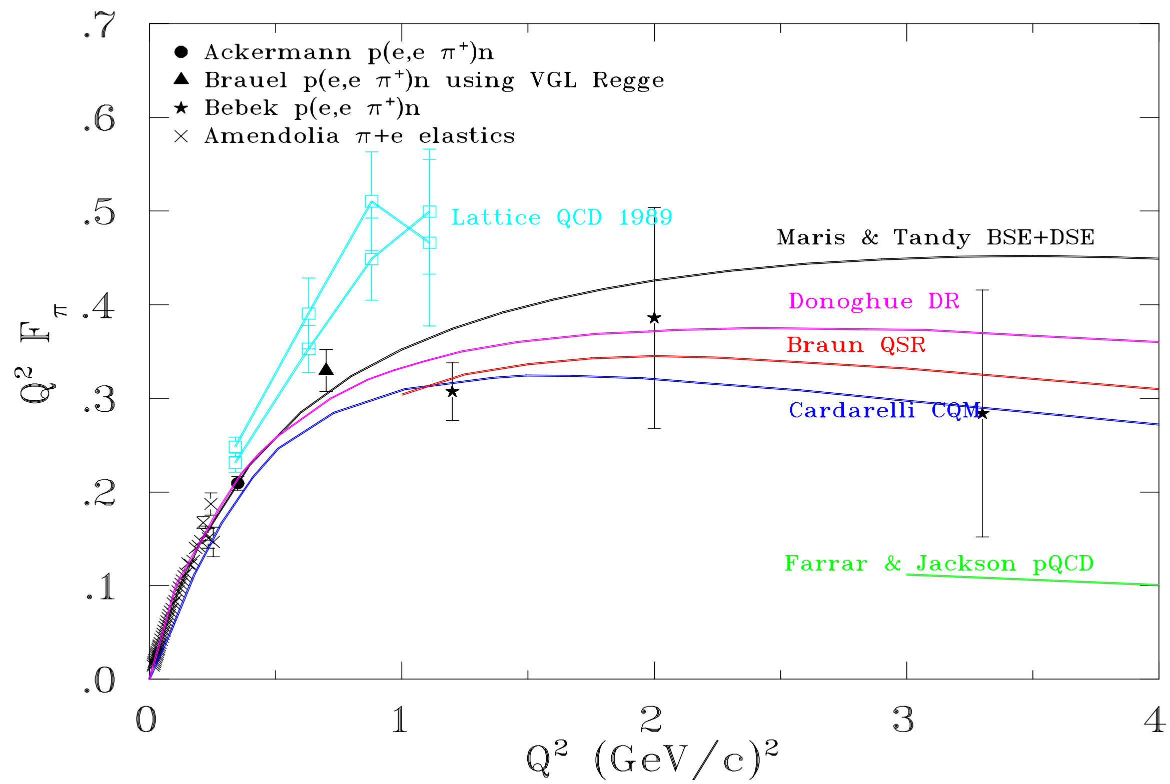
$$\sigma_L \propto \frac{-2tQ^2}{(t - m_\pi^2)^2} \cdot g_{\pi NN}^2(t) \cdot F_\pi^2$$

with σ_L dominating due to the proximity of the pole.

In practice one must extract F_π from a model which is gauge invariant, valid at large W to avoid the resonance region, and which accounts for rescattering. (More on this later.)

Pre-JLab F_π Dataset

$\pi + e$ elastics and high W electroproduction



- Pion elastic data have determined the pion charge radius.
- Lattice calculations and data differed systematically for $Q^2 \geq 0.5$.
- For $Q^2 \geq 1$, data were consistent with $Q^2 F_\pi \simeq$ *constant*.
- Error on the large Q^2 data are too large to permit model discrimination.

The need for better data, expecially at larger Q^2, was clear.

The Charged Pion Form Factor Collaboration

J. Volmer[18], K. Vansyoc[11], D. Abbott[17], J. Arrington[1], K. Assamagan[4], S. Avery[4], O.K. Baker[4,17], H. Blok[18], E.J. Brash[14], H. Breuer[7], R. Carlini[17], N. Chant[7], J. Dunne[17], R. Ent[17], D. Gaskell[12], R. Gilman[15,17], K. Gustafsson[7], W. Hinton[4], G.M. Huber[14], H. Jackson[1], M. Jones[2], C. Keppel[4,17], W.Y. Kim[6], A. Klein[11], D. Koltenuk[13], M. Liang[17], G.J. Lolos[14], A. Lung[17], D.J. Mack[17], D. McKee[9], D. Meekins[2], J. Mitchell[17], H. Mkrtchyan[19], G. Niculescu[4], I. Niculescu[4], D. Potterveld[1], J. Reinhold[1], S. Stepanyan[19], V. Tadevosyan[19], L.G. Tang[4,17], D. Vanwestrum[3], W. Vulcan[17], S. Wood[17], C. Yan[17], B. Zihlmann[17,]**

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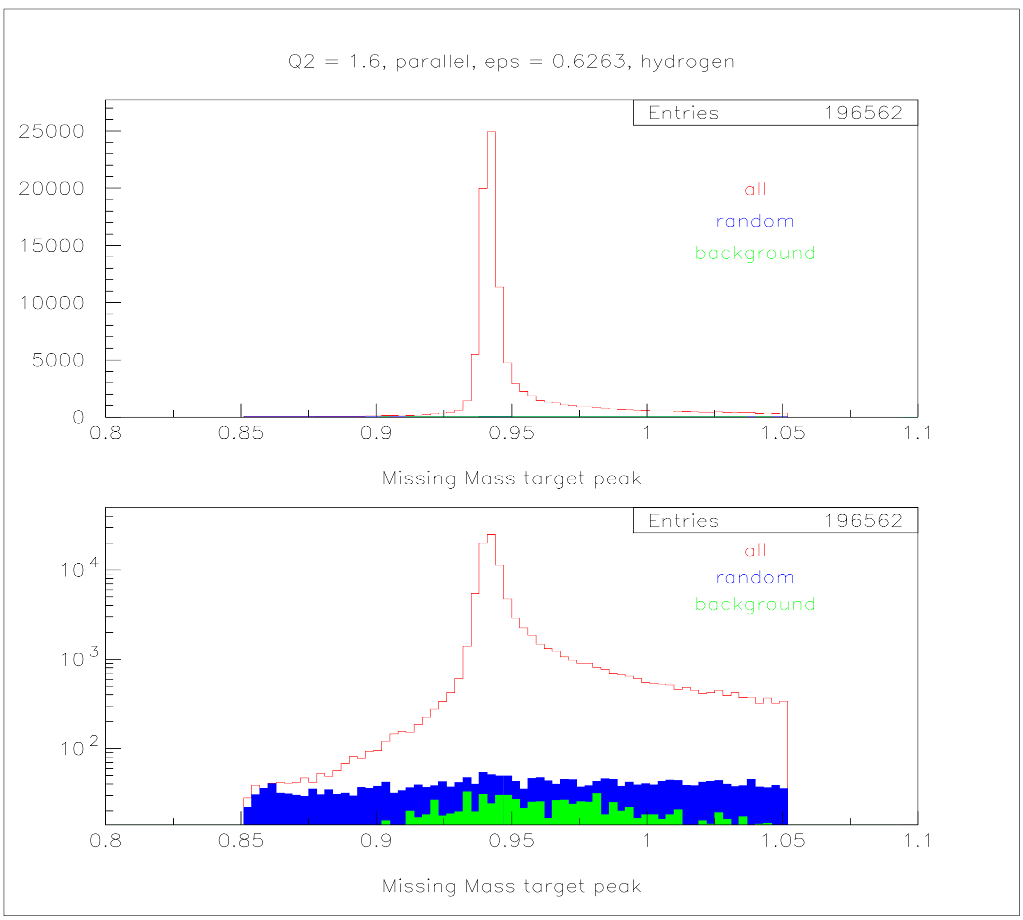
([*] and Florida International University)
([**] and University of Virginia)

Reconstructed Missing Mass: a Cut to Ensure Exclusivity

For the reaction e + p $\longrightarrow$ e' + π^+ + X,

$$MM_X = \sqrt{(e + p - e' - \pi^+)^2}$$

On linear and log scales, respectively, one finds

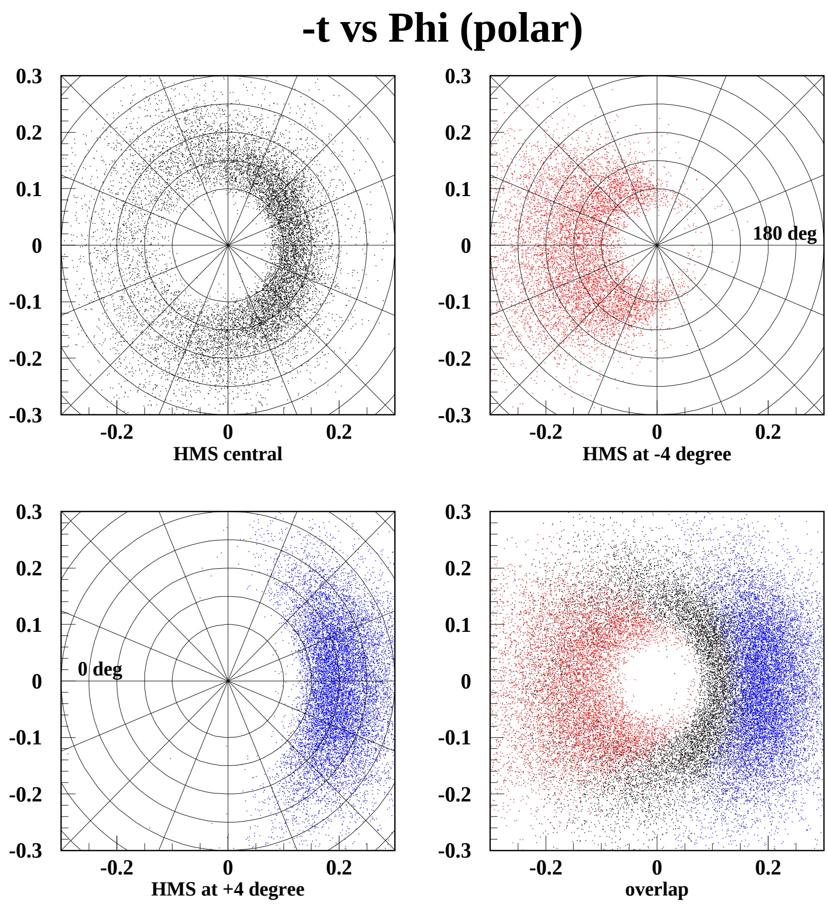


A cut which constrains $MM_X \simeq M_{neutron}$ removes backgrounds with higher inelasticity and suppresses random coincidences.

Extracting Response Functions from Cross Sections

$$\frac{d\sigma}{dt} = \sigma_T + \epsilon\,\sigma_L + \epsilon\cos 2\phi\,\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi\,\sigma_{LT}$$

Adequate coverage in $\phi_{q\pi}$ for each $-t$ bin is needed to separate the response functions. The pion spectrometer was scanned about $\vec{q}$.



A fit then determines $\sigma_T + \epsilon\,\sigma_L$, σ_{TT}, and σ_{LT}.

Reaction Mechanism Test: π^-/π^+ Ratios

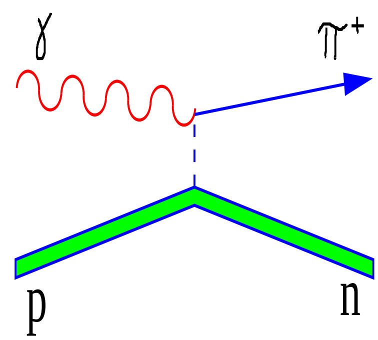
Using a Deuterium target, one can measure the ratio

$$R_L \equiv \frac{\sigma_L(\gamma + n \longrightarrow \pi^- + p)}{\sigma_L(\gamma + p \longrightarrow \pi^+ + n)}$$

Pion Exchange

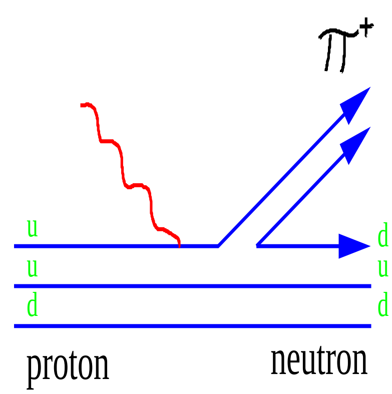
The coupling of γ_v to $\pi^\pm$ is the same magnitude. Assuming dominance of this amplitude

$$R_L \simeq \frac{Q^2_{\pi^-}}{Q^2_{\pi^+}} = 1$$



Quark Knockout

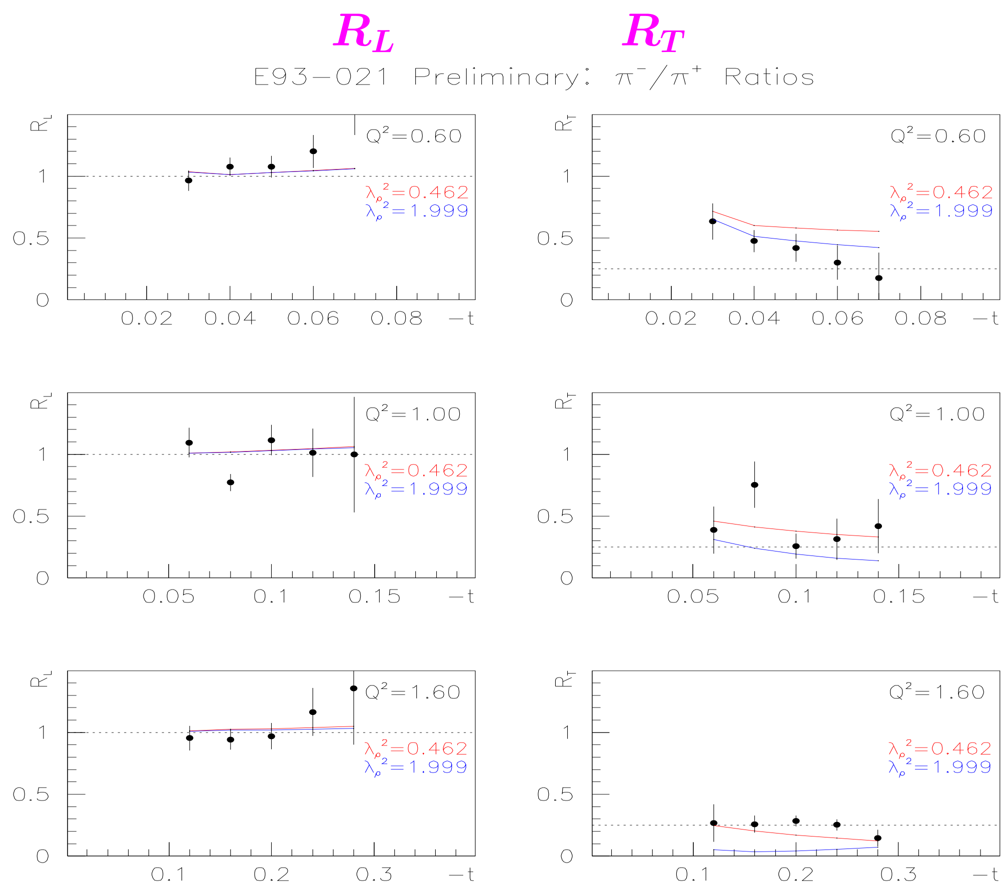
In this potential background scenario[8], forward π^- are the result of Q=-1/3 down quarks being knocked out of the neutron, and forward π^+ are the result of Q=+2/3 up quarks ejected from the proton. Assuming dominance,



$$R \simeq \frac{2Q_d^2}{2Q_u^2} = \frac{(-1/3)^2}{(+2/3)^2} = 1/4$$

[8] Carlson and Milana, PRL **65** 1717 (1990)

JLab First *Separated* π^-/π^+ Ratios: Test of the Reaction Mechanism



Longitudinal Ratio

The longitudinal ratio is $\simeq 1$ at low $-t$. This, combined with the strong $-t$ dependence of the longitudinal cross section, indicates pion pole dominance. Good news for F_π!

Transverse Ratio

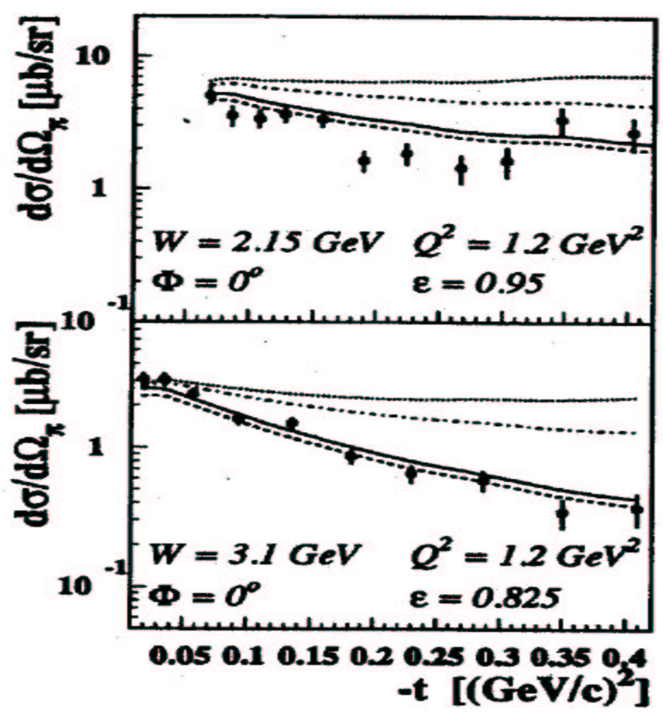
The transverse ratio is always less than 1, and with increasing Q^2 the ratio decreases until the naive quark model prediction of 1/4 is approached.

VGL Regge Model

To extract $F_\pi(Q^2)$ a model of pion electroproduction is needed which is valid at high W and has few free parameters. We chose the Regge model of Vanderhaeghen, Guidal, and Laget[11].

The coupling constants ($g_{\pi NN}$, $\rho_{\pi NN}$, etc.) were determined in their previous photoproduction work[12] leaving undetermined:

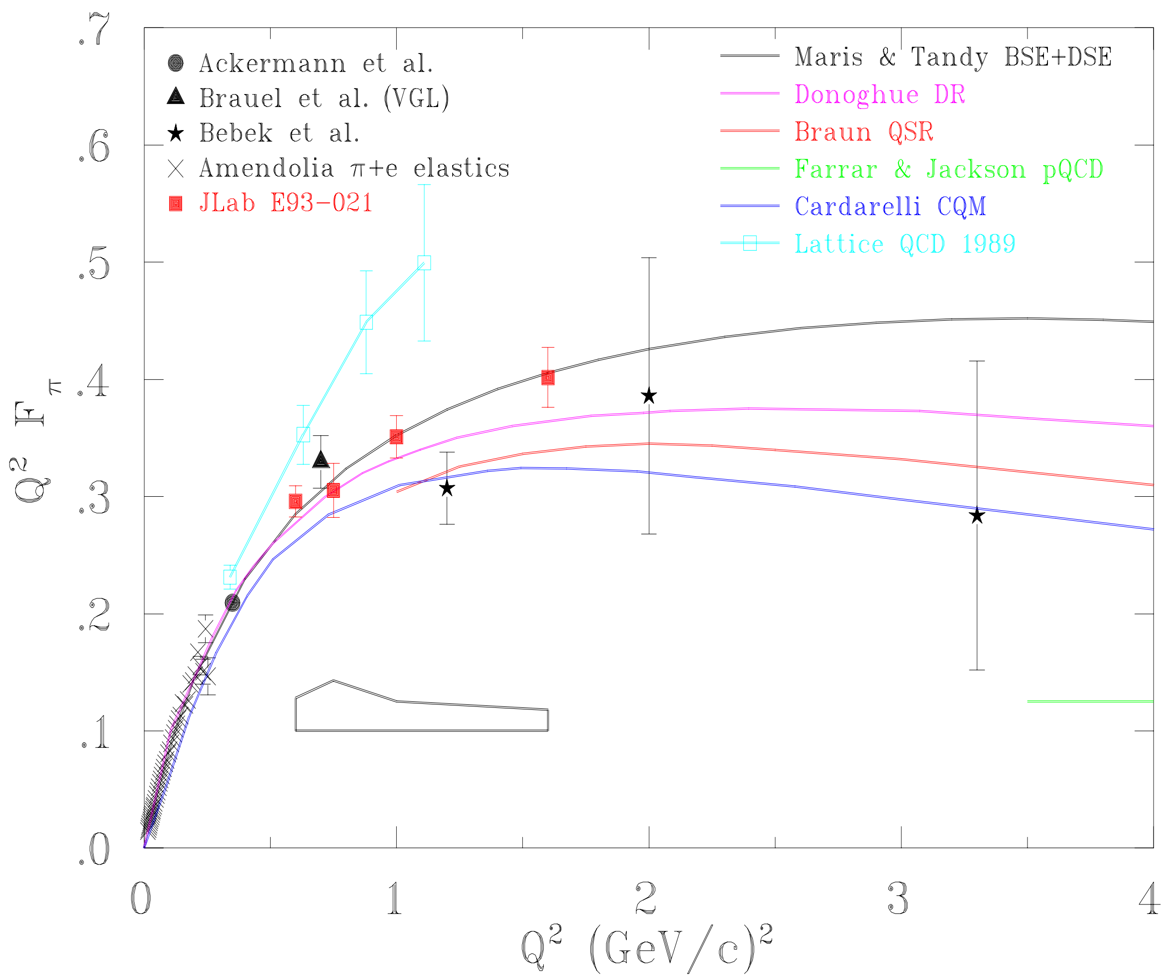
$$F_\pi(Q^2) \quad (\gamma^* \pi \to \pi)$$
$$F_\rho(Q^2) \quad (\gamma^* \rho \to \pi)$$



The full calculation describes the $-t$ dependence well (solid line).

[11] VGL, PRC **57**, 1454 (1998)
[12] GLV, PLB **400** (1997) 6-11

Present World Data for F_π



- Our higher Q^2 data[13] are larger than the trend of the older data.
- Low Q^2 lattice calculations need to be revisited.
- F_π is quite hard. The Maris and Tandy curve (which fits very well) is nearly indistinguishable from a monopole form factor which describes the pion radius.
- Many models fitted to the old data are systematically low. Serious models of F_π should have their free parameter(s) fitted to data in a different sector, and then used to *predict* F_π.

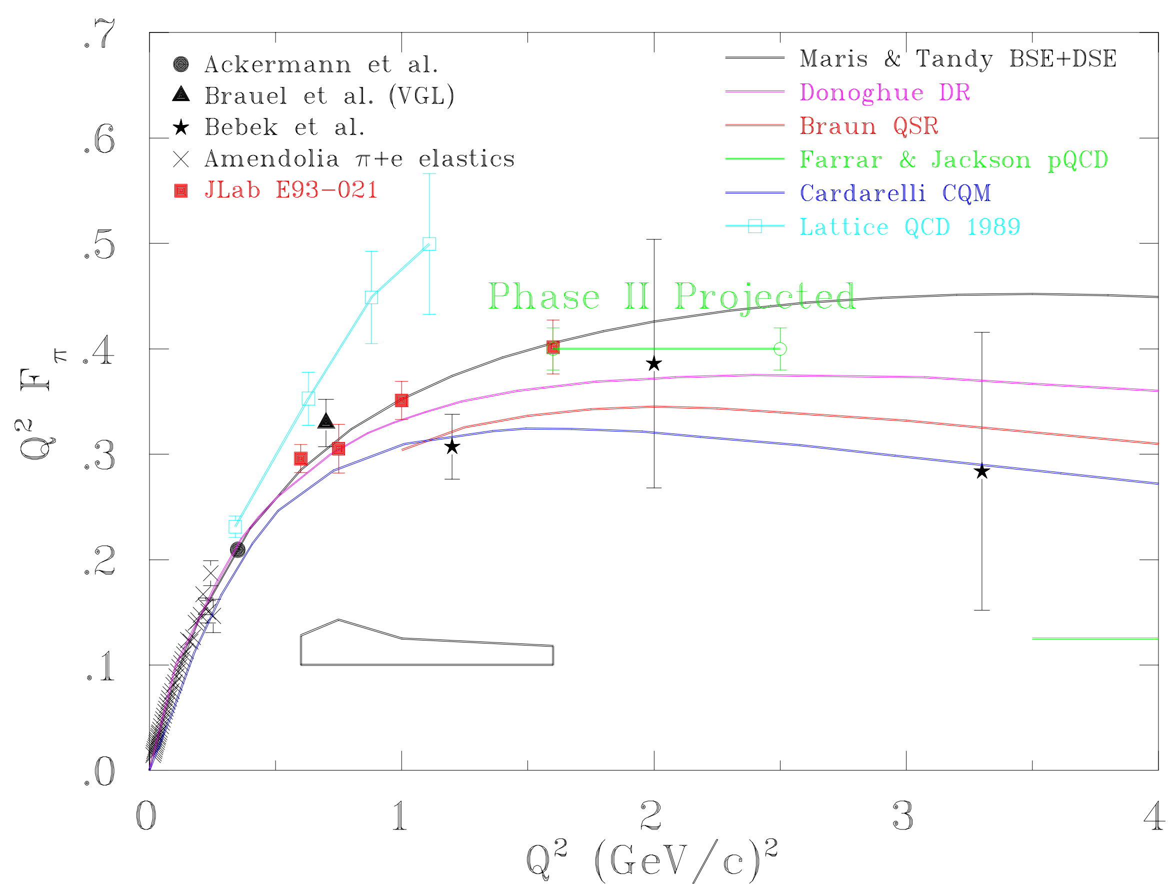
[13] J. Volmer et al, PRL 86, 1713 (2001)

What Else With 6 GeV Beam?

Phase II in 2003

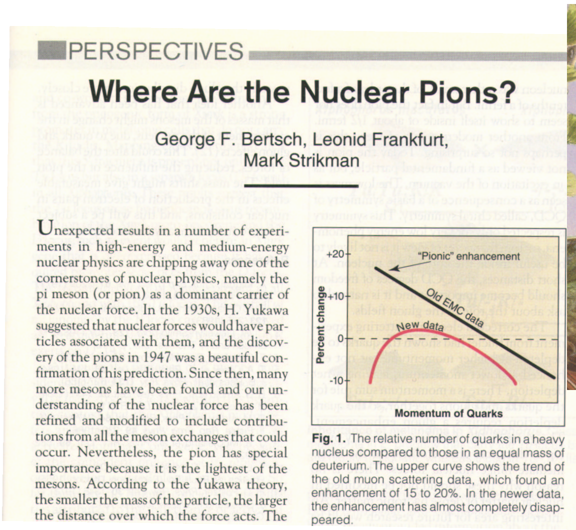
Our Phase I measurement was limited by 4 GeV beam. Our next measurements will be limited by spectrometer angle and momentum ranges. Our goals will be:

- **Increase our maximum Q^2 for F_π from 1.6 to 2.5**
- **Repeat Q^2=1.6 at higher W to study data vs Regge systematics.**



This will complete the HMS-SOS 6 GeV F_π program.

“Where are the Nuclear Pions?”



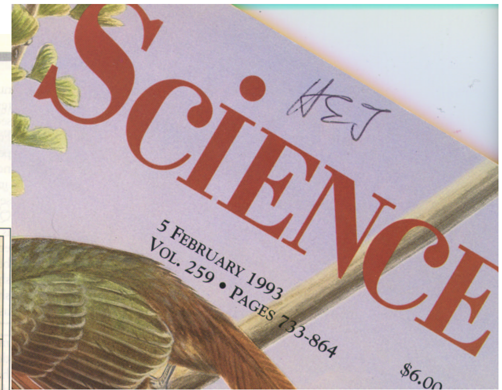
PERSPECTIVES

Where Are the Nuclear Pions?

George F. Bertsch, Leonid Frankfurt, Mark Strikman

Unexpected results in a number of experiments in high-energy and medium-energy nuclear physics are chipping away one of the cornerstones of nuclear physics, namely the pi meson (or pion) as a dominant carrier of the nuclear force. In the 1930s, H. Yukawa suggested that nuclear forces would have particles associated with them, and the discovery of the pions in 1947 was a beautiful confirmation of his prediction. Since then, many more mesons have been found and our understanding of the nuclear force has been refined and modified to include contributions from all the meson exchanges that could occur. Nevertheless, the pion has special importance because it is the lightest of the mesons. According to the Yukawa theory, the smaller the mass of the particle, the larger the distance over which the force acts. The

Fig. 1. The relative number of quarks in a heavy nucleus compared to those in an equal mass of deuterium. The upper curve shows the trend of the old muon scattering data, which found an enhancement of 15 to 20%. In the newer data, the enhancement has almost completely disappeared.

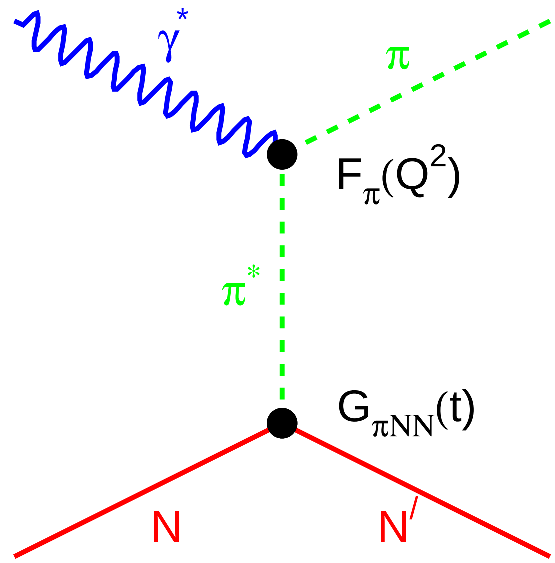


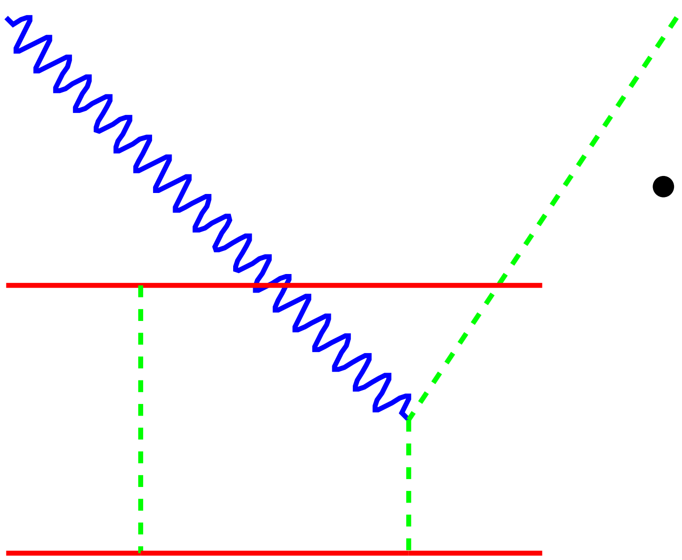
G. Bertsch, L. Frankfurt, and M. Strikman, Science **259**, 773 (1993)

- Yukawa theory - pions mediate the nuclear force
- Refined theory
  - → Additional mesons
  - → Form factors control pion contribution at short distances
  - → Pion contribution not large at short distances, but could still be important at intermediate distances
- 1983 - EMC sees mass dependence of F_2
- Later experiments interpreted as evidence for no (or small) pion excess
  - → Later DIS experiments see less mass dependence
  - → Drell-Yan sees no mass dependence
  - → $(\vec{p}, \vec{p}\,')$ and $(\vec{p}, \vec{n})$ see no mass dependence in R_L/R_T

Pion Electroproduction as Probe of Nuclear Pion Field

- Pole process single biggest piece of σ_L
- $G_{\pi NN}$ describes the probability for a nucleon to emit a virtual pion





- "Pionic enhancement" in nuclei would be perceived as an enhancement of $G_{\pi NN} \rightarrow$ enhancement of σ_L

E91003 Collaboration

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Separated Ratios

- Want to compare σ_L^H to $\int \frac{d\sigma_L^A}{dP_\pi}$ to look for signs of pion excess

- Target ratios may differ from 1 due to:

  → Incomplete P_π coverage: $\approx 80\%$ in deuterium at high k_π

  → Fermi motion of nucleon - leads to threshold effects and a shifting of the $\gamma^* N$ cross section strength

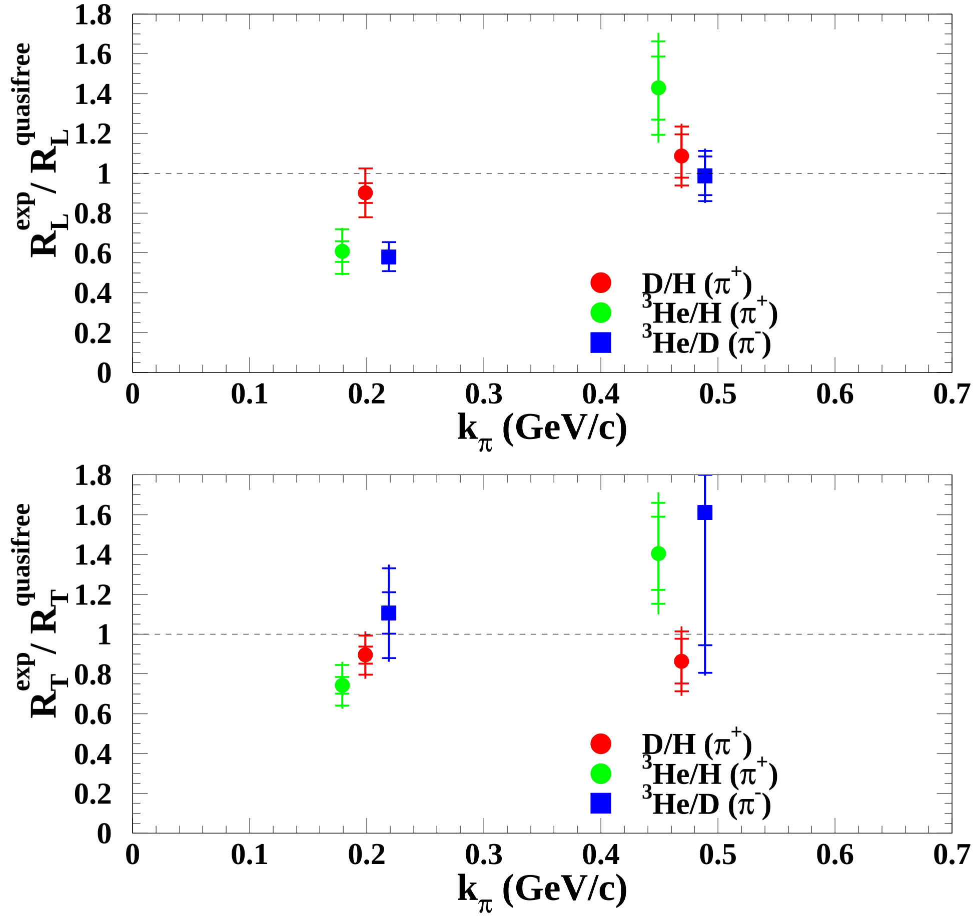
- Want to remove acceptance effects and "trivial" nuclear effects (Fermi motion)

- Analyze two ways

  → Extrapolate measured P_π distribution

  → Compare data to a simple calculation integrated over same region of P_π

Separated Ratios Compared to Quasifree Calculations



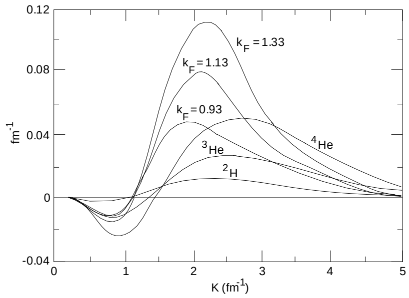
- These ratios measure deviation from quasifree production *over the region measured*

- Low k_π, ^{3}He π^+ includes Dn+pnn final states only: (coherent ^{3}He(e,e'π^+)^{3}H process contributes significantly (30%) to integrated cross section)

- At high k_π, ^{3}He π^+, ^{3}H final state suppressed by form factor - should only be $\approx$ 4-5% of H cross section

What Do We Expect from Pion Excess?

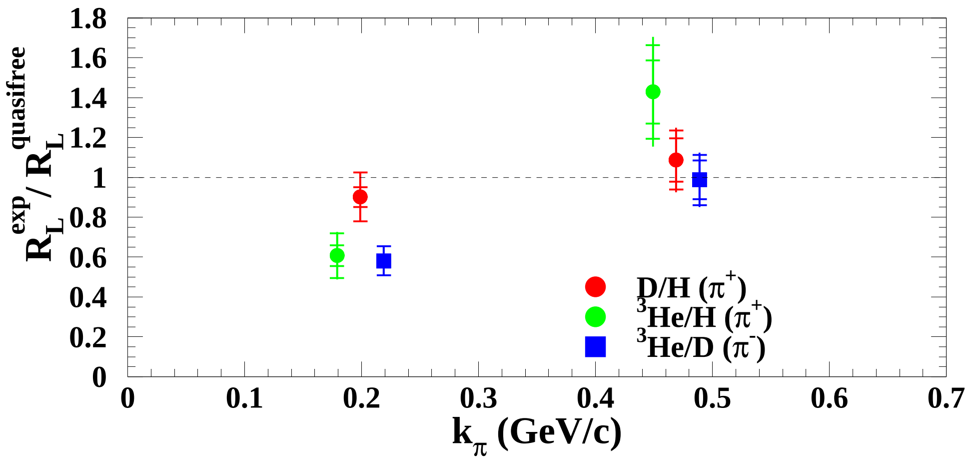
- Assume $\frac{\sigma_L^A}{\sigma_L^H} = \frac{n_\pi^N + \delta n_\pi^A}{n_\pi^N}$



- δn_π from Friman *et al.*

- n_π from simple field theory estimate (Henley and Thirring)

k_π (GeV/c)	D/H	^{3}He/H	^{3}He/D	^{4}He/H
0.20	0.99	0.86	0.88	0.69
0.47	1.06	1.13	1.07	1.24



- Results at high k_π not inconsistent with this simple estimate - but ^{3}He results at low k_π more suppressed than estimate

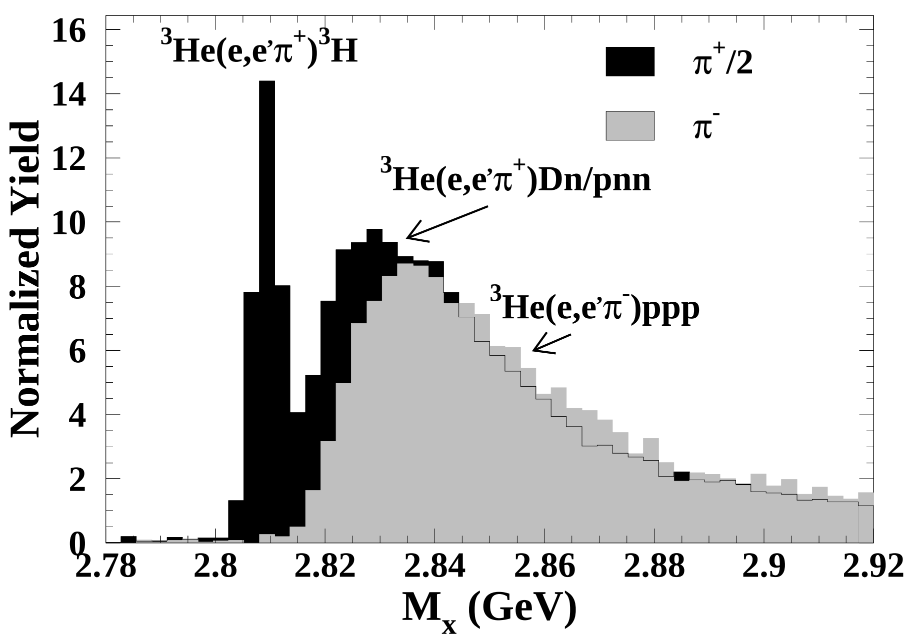
JLAB Measurement of ^{3}He$(e, e'\pi^+)^3$H

- Earlier Mainz measurement found:

$\rightarrow$ Larger than (naively) expected σ_L
– attributed to medium modifications to pion propagator

$\rightarrow$ Smaller than expected σ_T
– attributed to broadening of Δ

- JLAB E91003 got ^{3}H data "for free" at low k_π point



$\rightarrow$ Final pion momentum large ($p_\pi \approx 1$ Gev$/c$) so final state interactions small

$\rightarrow$ Also have proton data at same kinematics - can make direct comparison to extract target–dependence

JLAB ^{3}He$(e, e'\pi^+)^3$H Results

- Simple prediction gives: $\frac{\sigma(^3H)}{\sigma(H)} = \rho F^2(k) = 0.42$
  ρ = correction due to difference in density of final states
  $F^2(k)$ = ^{3}He form factor squared

- Results for unseparated cross sections:

ϵ	R=$\sigma(^3H)/\sigma(H)$
0.49	0.34 $\pm$ 0.01 $\pm$ 0.01
0.89	0.38 $\pm$ 0.01 $\pm$ 0.02

- Results for separated cross sections:

L or T	R=$\sigma(^3H)/\sigma(H)$
σ_L	0.50 $\pm$ 0.04 $\pm$ 0.07
σ_T	0.24 $\pm$ 0.04 $\pm$ 0.04

- Longitudinal and transverse ratios suppressed quite differently $\rightarrow$ consistent with Mainz results where they saw MORE (LESS) longitudinal (transverse) strength than expected.

- Need detailed calculations to see if similar modification of pion propagator and resonance widths explain effect

Future Measurements

- Proposal was submitted to do NucPi experiment at more optimal kinematics (higher W, higher P_π, better M_x coverage, etc.) but was rejected.

- Color transparency using $A(e, e'\pi^+)$

- F_π at 12 GeV

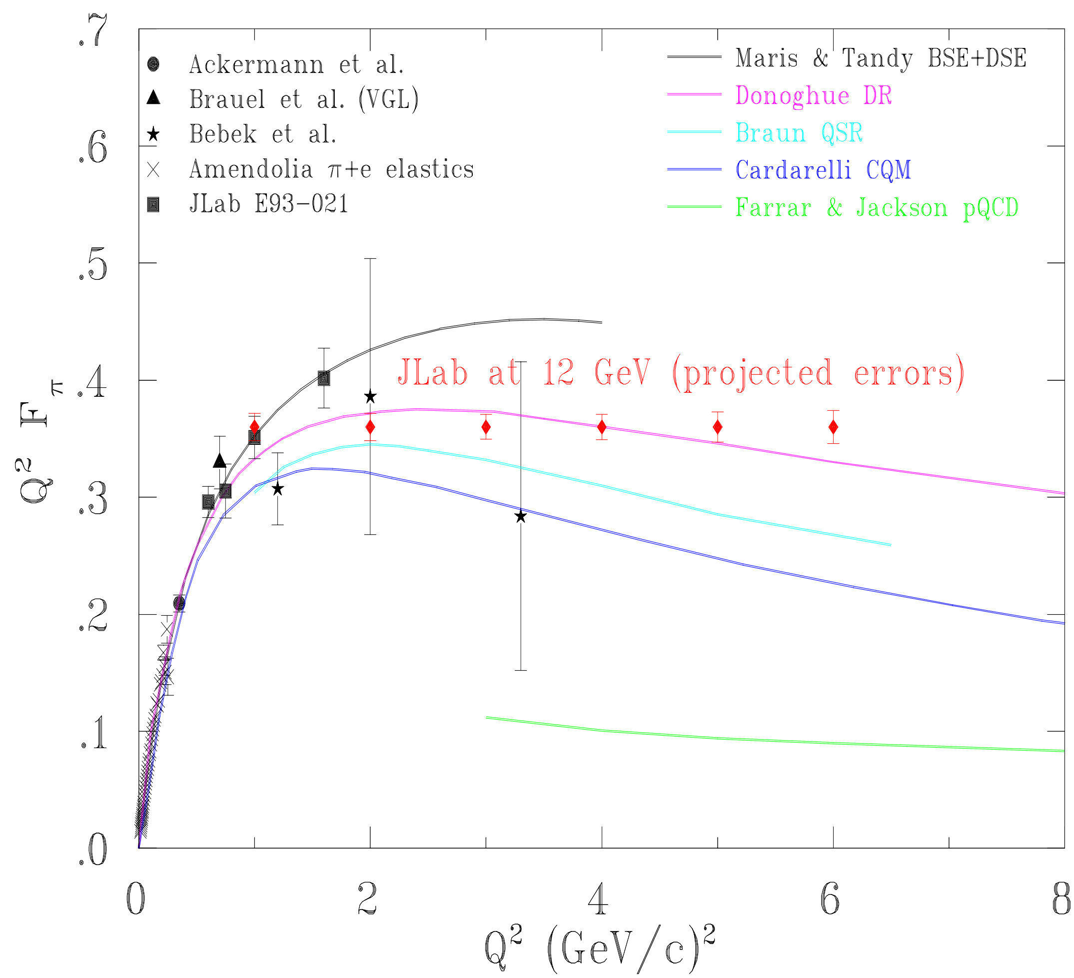
- Factorization tests: $\sigma_L \propto 1/Q^6$?

- Azimuthal dependence of transverse target asymmetry

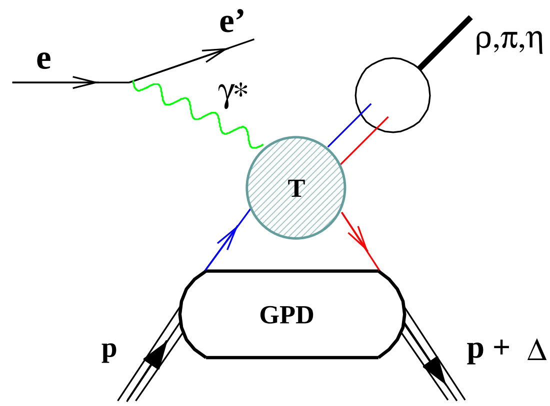
Projected Errors for F_π at 12 GeV

Running Conditions

- HMS-SHMS
- 100 days
- 4cm LH_2 target
- 50 μA

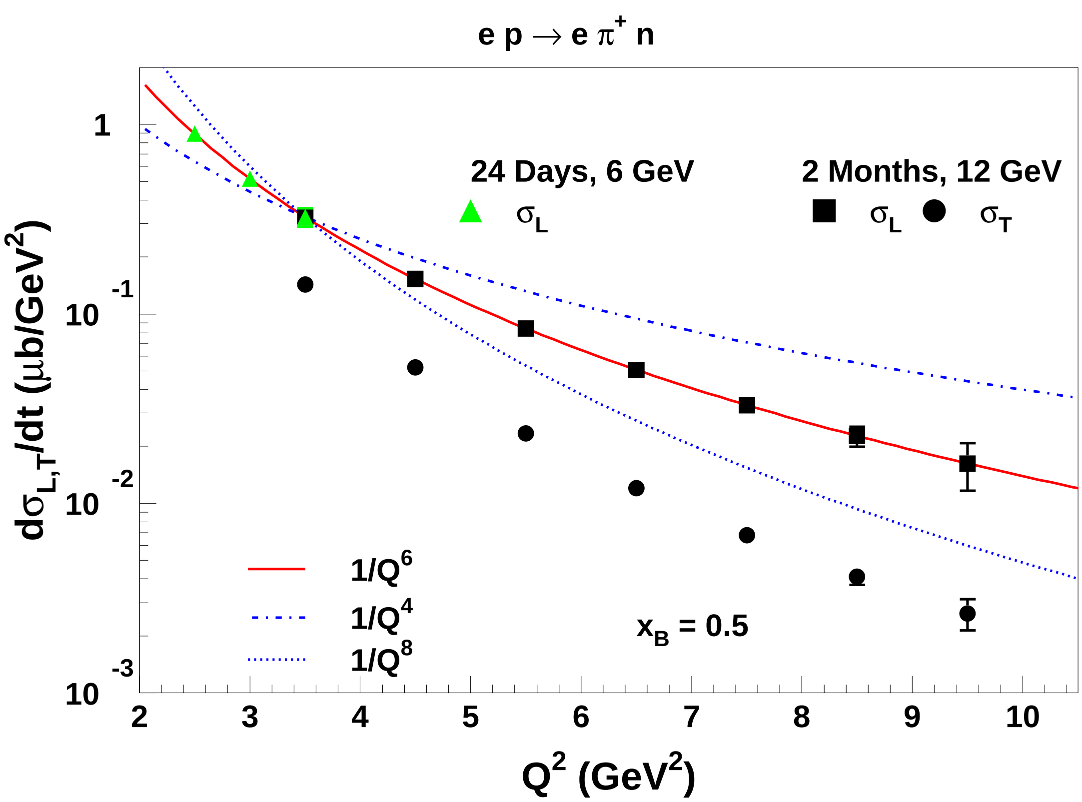


Factorization Tests



- GPD measurements rely on soft–hard factorization

- Perhaps the most rigorous test is observation (or not) of expected $1/Q^6$ dependence of longitudinal cross section



Transverse Target Asymmetry

$$A_{UT} = \frac{\int_0^{\pi} d\beta \frac{d\sigma_L^{\pi^+}}{d\beta} - \int_{\pi}^{2\pi} d\beta \frac{d\sigma_L^{\pi^+}}{d\beta}}{\int_0^{2\pi} d\beta \frac{d\sigma_L^{\pi^+}}{d\beta}}$$

$\beta =$ angle between target polarization vector and reaction plane

- π^+ Transverse Target Asymmetry sensitive to interference of $\widetilde{E}$ and $\widetilde{H}$ GPD's

- May be able to measure in Hall C using BETA (see Glen Warren's talk) and the UVa polarized target

- To unambiguously extract contribution from longitudinal photons, would require L–T separation